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International application number: PCT/US05/005597

International filing date: 24 February 2005 (24.02.2005)

Document type: Certified copy of priority document

Document details: Country/Office: US
Number: 60/562,652
Filing date: 15 April 2004 (15.04.2004)

Date of receipt at the International Bureau: 31 March 2005 (31.03.2005)

Remark: Priority document submitted or transmitted to the International Bureau in compliance with Rule 17.1(a) or (b)

World Intellectual Property Organization (WIPO) - Geneva, Switzerland
Organisation Mondiale de la Propriété Intellectuelle (OMPI) - Genève, Suisse

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APPLICATION NUMBER: ***60/562,652***
FILING DATE: ***April 15, 2004***
RELATED PCT APPLICATION NUMBER: ***PCT/US05/05597***

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22713 U.S. PTO
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PROVISIONAL APPLICATION FOR PATENT COVER SHEET

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

Express Mail Label No. ER 769693331 US

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15535 U.S. PTO
60/562652
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☐ Additional inventors are being named on the ____ separately numbered sheets attached hereto

TITLE OF THE INVENTION (280 characters max)

Heterodyne Downmixing Detection of Radio-Frequency Piezoresistive Nanoelctromechanical Systems

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ENCLOSED APPLICATION PARTS (check all that apply)

☒ Specification Number of Pages 2

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☐ Application Data Sheet. See 37 CFR 1.76

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☒ Applicant claims small entity status. See 37 CFR 1.27.

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FILING FEE AMOUNT ($): 80

The invention was made by an agency of the United States Government or under a contract with an agency of the United States Government.

☐ No

☒ Yes, the name of the U.S. Government agency and the contract number are: **Grant No. N00014-02-1-0602 awarded by the DARPA**

Respectfully submitted,

SIGNATURE ________________

Date 4/15/2004

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Heterodyne Downmixing Detection of Radio-Frequency Piezoresistive Nanoelectromechanical Systems

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Abstract

We have developed a method of measuring the MHz-range resonance properties of nanoelectromechanical systems (NEMS) with integrated piezoresistors. The technique takes advantage of the high strain sensitivity of semiconductor-based piezoresistors, while overcoming the problem of high-impedance RF signal attenuation. Our technique also greatly reduces crosstalk between the detector and actuator circuits. We use this method to study the resonance properties of high-frequency cantilever resonators.

Introduction

The study of microelectromechanical systems (MEMS) has been increasing in recent years in both the scientific and technological realms. Recent work has extended this field to nanoelectromechanical systems (NEMS), where the device dimensions are submicron in size and the resonant frequencies are in the MHz or even GHz range. A useful method for detecting displacement in MEMS utilizes semiconductor-based piezoresistive strain sensors integrated directly into the device. However, there has been difficulty in applying piezoresistive detection to high-frequency NEMS devices, due to the intrinsically high resistances of the piezoresistor (5-100 kΩ), which leads to significant signal attenuation at MHz frequencies with DC biasing schemes. Such attenuation will pose a significant detection problem as the frequencies are increased to the GHz range and beyond.

Our technique overcomes the problem of high-frequency attenuation by utilizing AC biasing and the intrinsic properties of the piezoresistor to perform heterodyne downmixing of the signal to a lower frequency, which can then be detected by standard circuitry without significant signal loss. Not only does this increase the detected signal, it greatly reduces unwanted background from crosstalk between the detector and actuator circuits. As proof of principle, we have applied this downmixing scheme to the detection of cantilever NEMS with fundamental resonance frequencies of 10-25 MHz. We demonstrate thermomechanical-noise-limited displacement detection in these devices, indicating that downmixed piezoresistive signal detection is a viable technique in high-frequency NEMS applications.

Circuit Design

Figure 1 displays a schematic of the NEMS actuation and detection circuit we have developed. The piezoresistor R_c is placed in a half-bridge configuration with a fixed dummy resistor R_d; for simplicity we will assume here $R_c = R_d = R$ when the NEMS is at rest. Through the use of an AC voltage source and a

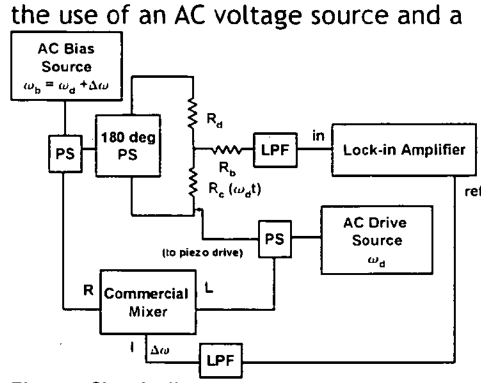

Fig. 1: Circuit diagram.

180 deg power splitter (PS), the ends of the resistors are oppositely biased, at $+(V_b/2)\cos(\omega_b t)$ and $-(V_b/2)\cos(\omega_b t)$, so that the voltage at the bridge point is zero when the NEMS is not moving. The motion of the NEMS is driven with a second AC voltage source at a frequency ω_d that is offset from ω_b by an amount $\Delta\omega = \omega_b - \omega_d$. With the drive the NEMS resistance varies in time: $R_c = R + \Delta R\cos(\omega_d t + \phi)$, $R >> \Delta R$. To leading order in $\Delta R/R$, the voltage at the bridge point V_{out} is

$$V_{out}(t) = \frac{V_b\left(R + \Delta R\cos(\omega_d t + \phi)\right)}{2R + \Delta R\cos(\omega_d t + \phi)} - \frac{V_b}{2} \quad (1)$$

$$\approx \frac{V_b\cos(\omega_b t)}{4R}\left(\Delta R\cos(\omega_d t + \phi)\right) \quad (2)$$

$$\approx V_b\frac{\Delta R}{8R}\left[\cos(\Delta\omega t - \phi) + \cos((2\omega_d + \Delta\omega)t + \phi)\right] \quad (3)$$

Thus the output signal is split into two frequency components, each with half the power of the original signal. With

$\Delta\omega$ kept small (< 100 kHz), attenuation due to parallel capacitances can be minimized. The output is passed through a bridge resistor R_b, which keeps the RF bias from being shorted by parallel capacitances. The output is then sent through a low pass filter (LPF) to remove the residual carrier and the upper sideband, and fed into a lock-in amplifier for detection. The lock-in reference is generated by splitting off the bias and drive voltages with power splitters (PS) and sending the voltages into a commercial mixer, which generates a downmixed signal in parallel with the NEMS.

Demonstration

We have tested the downmixing scheme using high-frequency piezoresistive cantilevers as the NEMS device. These cantilevers consist of 80 nm silicon + 30 nm p+Si grown epitaxially on SiO_2, and defined through a combination of deep reactive ion etching, electron-beam lithography, and fluorine/chlorine-based plasma etching; the details of fabrication can be found elsewhere (1). A cantilever is shown in Fig. 3a, with the full device layout (including on-chip bridge and dummy resistors) shown in Fig. 3b. The devices ranged from 2-3 microns in length, yielding fundamental mode vibration frequencies of 10-25 MHz. The devices were mounted onto a piezoceramic actuator disk, and were measured at room temperature in a vacuum chamber.

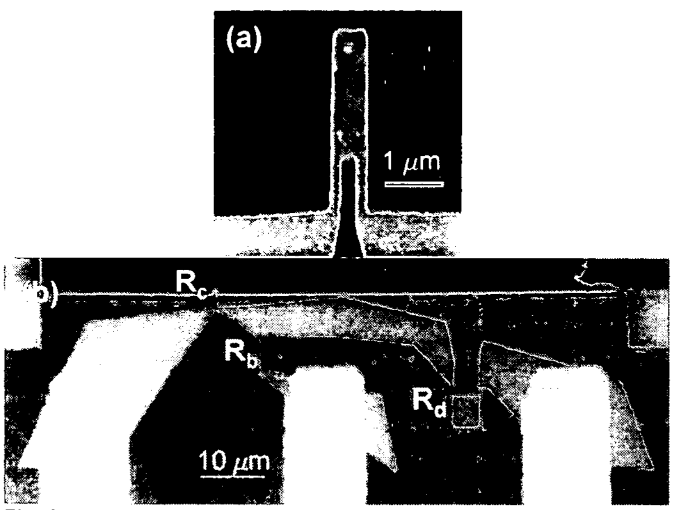

Fig. 2: (a) Closeup of cantilever; (b) full resistor layout.

Figure 3a displays a resonance curve for a 2.6 micron-long cantilever, measured using our downmixing circuit by varying the drive and bias frequencies simultaneously so as to keep the offset frequency constant. Here V_b = 5 V peak to peak, $\Delta\omega$ = 100 kHz, and a peak-to-peak voltage of 3 V is applied to the piezo actuator. For comparison, Fig. 3b displays the magnitude and phase measured by applying a DC bias (5 V) across the resistors, and directly measuring the RF signal at the bridge point using a network analyzer for drive (15 dBm) and detection. Two things are noticeable. First, the voltage amplitude at the amplifier is several orders of magnitude smaller in the direct measurement setup vs. the downmixing circuit, despite the comparable levels of bias and drive. Second, the background in the direct measurement setup is much larger relative to the signal, due to direct electrical crosstalk of the drive circuit with the measurement circuit. This distorts the shape of the measured amplitude and phase curves. Downmixing greatly reduces such crosstalk, giving much cleaner resonance curves.

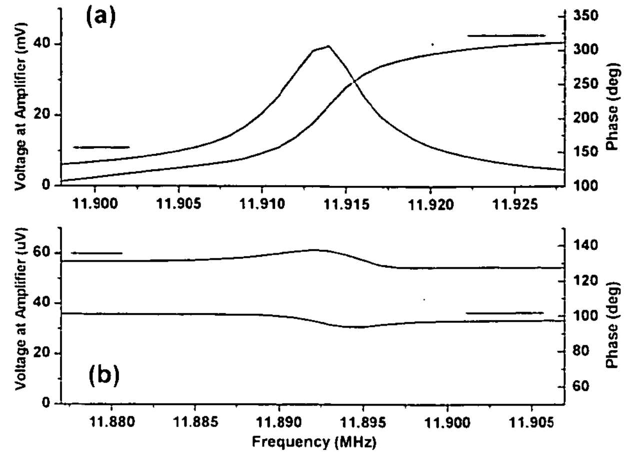

Fig. 3: (a) Amplitude and phase of RF cantilever resonance of cantilever NEMS, measured with downmixing; (b) Same cantilever measured directly with DC bias and a network analyzer.

Figure 4 demonstrates that we can reach the ultimate sensitivity limit of thermomechanical noise using the downmixing technique. This noise (from the same device as used in Fig. 3) was measured by turning off the drive and sweeping the frequency of the bias, while detecting narrowband noise at 50 kHz using the noise mode of the lock-in amplifier. The noise appears as two peaks spaced 100 kHz apart, as the noise in the cantilever at the resonance frequency is mixed to the 50 kHz reference frequency when the bias is either 50 kHz above or below the cantilever frequency.

The circuit has sufficient sensitivity that we can even detect the thermal noise component at the second vibration mode of this cantilever, at 71 MHz; this is shown in the inset. Thus our downmixing technique is likely suitable for even smaller NEMS devices with higher fundamental mode frequencies.

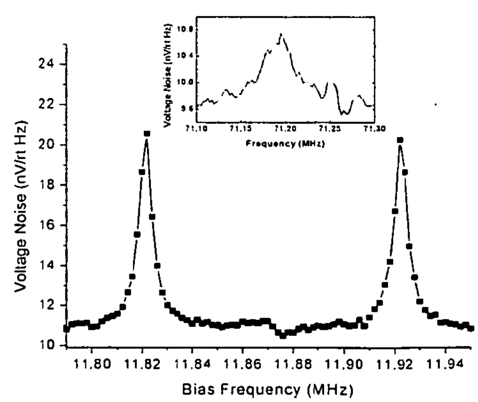

Fig. 4: Thermomechanical noise peaks of fundamental vibration mode of cantilever NEMS. Inset: one of the noise peaks of second vibration mode of same cantilever.

References

1. J. L. Arlett et al, Preprint